TECH. NOTE
ARM.634

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INVENTORY 1971

ROYAL AIRCRAFT ESTABLISHMENT

(FARNBOROUGH)

TECHNICAL NOTE No: ARM.634

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SOME NOTES ON THE POSSIBLE APPLICATION OF THERMOELECTRIC DEVICES TO GUIDED MISSILE FUZING PROJECTS

by

P.J.BATEMAN, B.Sc., Grad.Inst.P.

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Technical Note No. Arm.634
February, 1959

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(FARNBOROUGH)

SOME NOTES ON THE POSSIBLE APPLICATION OF THERMOELECTRIC DEVICES TO GUIDED MISSILE FUZING PROJECTS

by

P. J. Bateman, B.Sc., Grad.Inst.P.

RAE Ref: Arm/2753/PJB

SUMMARY

Using semiconductor materials which have recently been developed, it should be possible to produce thermoelectric devices which will give a power output per unit weight comparable with that of conventional power sources. This can only be realised in practice if installation problems can be overcome, and the effective hot and cold junctions are of order 1 cm apart. Refrigeration and thermostatic applications may also be practicable.

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1 INTRODUCTION

If two dissimilar materials are connected to each other at two points to form an electric circuit, and the two junctions are maintained at different temperatures then, depending on the thermoelectric properties of the two materials, a current will flow in the electric circuit. If a resistive load is now included in the circuit, electrical energy will be dissipated in the load. A thermoelectric generator of this type may have application in guided missile fuzing systems where waste heat, available from jet pipe exhaust or kinetic heating, may be converted directly into electrical energy and used to supply or control devices within a missile. Since the thermoelectric effects are reversible they might also be applied to local refrigeration or temperature control systems.

It is the purpose of this note to examine the possibilities offered by thermoelectric devices and to discuss the present position and future prospects in the field in this country.

2 THE NATURE OF THE THERMOELECTRIC EFFECT

When a circuit is formed by two dissimilar materials and the junctions are maintained at different temperatures by some external agency, two types of thermoelectric effect may be apparent:-

(1) The Seebeck effect

This gives rise to an electromotive force in the circuit by virtue of the temperature difference between the two junctions. The reverse effect, known as the Peltier effect, causes heat to be emitted at one junction and absorbed at the other when an electric current is passed through the circuit.

(2) The Thomson effect

This gives rise to an e.m.f. in any element of material which supports a temperature gradient. This effect is usually small compared with the Seebeck effect over the range of temperature differences for which thermocouples may most usefully be employed.

The ratio of change of the total e.m.f. in the circuit with change in temperature difference between the junctions is known as the Thermoelectric Power α of the circuit.

The Efficiency η of a thermoelectric generator is the percentage of the rate of consumption of thermal energy which is delivered to the load as electrical power. Thus for a generator of high efficiency, materials are required which have a high value of thermoelectric power α and which have low values of thermal conductivity k, so that for a fixed temperature difference between the hot and cold junctions a minimum of heat will be lost irreversibly by conduction down the branches. For a given load the maximum efficiency is achieved with a generator having minimum internal impedance; this demands thermoelectric materials of low specific resistivity ρ.

It can be shown that the parameter $Z = \frac{\alpha^2}{k\rho}$ is a convenient figure of merit with which to describe thermoelectric materials. (Refs.1 and 2*.)

---

* Some British workers use the square root of this value, viz. $\frac{\alpha}{\sqrt{k\rho}}$.

The most suitable metals with $\alpha \sim 40\ \mu V/^{\circ}C$ have a value of Z around $0.3 \times 10^{-3}/^{\circ}C$ which leads to efficiencies of only 1% for generators using these materials. Thermoelectric generators really only become a practical proposition when efficiencies approaching 10% can be achieved and, with existing semi-conductor materials which have values of Z greater than 1×10^{-3}, this should be possible.

3 THE CHOICE OF THERMOELECTRIC MATERIALS

The properties which affect the figure of merit are all functions of the carrier concentration n, that is, electrons or, in the case of some semi-conductors, "positive holes". The electrical conductivity $\sigma = \frac{1}{\rho}$ is roughly proportional to n whilst the thermoelectric power α tends to zero when n tends to infinity, and α tends to infinity when n goes to zero. But when n is reduced to zero ρ is very large and hence the figure of merit might not be increased. Electron theory indicates that $\frac{\alpha^2}{\rho}$ will be a maximum when $n \sim 10^{19}\ cm^{-3}$, which is 1000 times smaller than for metals and is in the realm of semiconductors. It can be shown also that the optimum value for α is around $200\ \mu V/^{\circ}C$. The thermal conductivity k of a substance is the sum of two parts: that due to the free carriers k_{el} and proportional to n, and that due to lattice vibrations k_{ph} (phonons) which is independent of n. At the concentration $n = 10^{19}\ cm^{-3}$, k_{el} is small. For a large figure of merit Z to be obtained, a high value of the ratio $\frac{\sigma}{k}$ is required coupled with a large value of α. The minimum value of k is given by k_{ph}, which is obtained when n is zero, but we must accept a small n since σ must be as large as possible. Now $\sigma = n u e$, where u is the carrier mobility and e is the carrier charge, so we need carriers of high mobility. High values of u are found in inter-metallic compounds of medium atomic weight, e.g. indium antimonide, and low values of k_{ph} are found in compounds and alloys of the heavy elements particularly in the middle groups of the periodic system.

Since α^2 varies more rapidly with n than do σ and k, it is possible to "dope" the material with carriers (assuming there were too few carriers present initially) to give a favourable value of α. This treatment may also increase the ratio $\frac{\sigma}{k}$, which may be further improved by a reduction of the lattice thermal conductivity k_{ph} by the addition of an impurity compound which crystallises into the lattice in such a way that phonons are scattered, but electrons, with their longer wavelengths, are not affected, and their mobility is unaltered*.

The materials used for thermoelectric generation are intermetallics of Pb, Hg, Bi, Tl and possibly Sb, with Te, Se and S. The most advantageous arrangement is for one branch of each thermocouple to be an n-type semiconductor (having an excess of carrier electrons) and the other to be a p-type semi-conductor (having a deficit of carrier electrons, that is, an excess of positive holes). Bismuth Telluride has been gradually developed (Refs.3-7) until an alloy $Bi_2Te_3 - Sb_2Te_3$ has now been produced which gives an overall figure of merit for a p-n junction of $2.4 \times 10^{-3}/^{\circ}C$. If this could be incorporated into a generator with the junctions operated at 600°K and 300°K the optimum efficiency of the device would be 11.4%.

---

* Up till 1954 materials of high thermoelectric power had been selected and an impurity added to decrease the resistivity and also the brittleness (Ref.8).

Given a material of high figure of merit, it might be possible to reduce the thermal conductivity without affecting the electrical conductivity by obtaining the material in powdered or laminated form.

4 THE APPLICATION TO A THERMOELECTRIC GENERATOR

The efficiency of a thermoelectric generator η is given by $\eta = \frac{W}{Q_a}$, where W is the useful electrical power delivered to the load, and Q_a is the net amount of heat absorbed by the hot junction per unit time.

Considering a single thermocouple connected to a load R, we have that, following Ioffe (Ref.1):-

$$\eta = \frac{W}{Q_a} = \frac{W}{Q_1 + Q_h - \frac{1}{2} I^2 r} \qquad (1)$$

where Q_1 is the rate at which Peltier heat is absorbed at the hot junction at temperature T_1 due to the current I passing through the circuit. This is equal to $\alpha I T_1$. Q_h is the rate at which heat is conducted down the branches from the hot junction to the cold junction at temperature T_o.

Thus

$$Q_h = (k_1 S_1 + k_2 S_2) \left(\frac{T_1 - T_o}{L}\right) = K\,(T_1 - T_o) \qquad (2)$$

where k_1, k_2 and S_1, S_2 are the thermal conductivities and cross-sectional areas of the two branches respectively, and L is their length. K is therefore a lumped constant. The term $\frac{1}{2} I^2 r$ in equation (1) represents half the Joule heat which is dissipated within the thermocouple of impedance r and which appears at the hot junction.

Now

$$I = \frac{\alpha(T_1 - T_o)}{R + r}$$

where R is the load impedance and putting $m = \frac{R}{r}$, we obtain

$$Q_1 = \frac{\alpha^2\, T_1\, (T_1 - T_o)}{r\,(m+1)}$$

and

$$W = \frac{\alpha^2\, (T_1 - T_o)^2\, m}{r\,(m+1)^2}.$$

Substituting these values in equation (1) we get

$$\eta = \frac{T_1 - T_o}{T_1} \cdot \frac{\frac{m}{m+1}}{1 + \frac{Kr}{\alpha^2} \cdot \frac{m+1}{T_1} - \frac{T_1 - T_o}{2T_1 (m+1)}} . \qquad (3)$$

For an arbitrary value of m the maximum efficiency is given when Kr is a minimum and this occurs when

$$\frac{\rho_1 k_2}{\rho_2 k_1} = \left(\frac{S_1}{S_2}\right)^2$$

whence

$$Kr = \left(\sqrt{k_1 \rho_1} + \sqrt{k_2 \rho_2}\right)^2 \quad \text{and} \quad z = \frac{\alpha^2}{\left(\sqrt{k_1 \rho_1} + \sqrt{k_2 \rho_2}\right)^2} .$$

For a given value of internal resistance r, the maximum delivery of power occurs when R = r; but the maximum efficiency occurs for R > r, in fact, for a value of m given by $\left(\frac{R}{r}\right)_{opt} = M = \sqrt{1 + \frac{1}{2} z (T_1 + T_o)}$. (4)

In practice M will vary between 1 and 2. The gain in efficiency obtained by optimising the ratio $\frac{R}{r}$ rather than taking R = r may be up to 1% of the total energy dissipated. When R = r the efficiency is given by

$$\eta = \frac{T_1 - T_o}{T_1} \cdot \frac{2T_1 z}{8 + z (3T_1 - T_o)} . \qquad (5)$$

Substituting the value of z obtained from equation (4) into equation (3) we get

$$\eta_{opt} = \frac{T_1 - T_o}{T_1} \cdot \frac{M - 1}{M + \frac{T_o}{T_1}} \qquad (6)$$

which indicates that the optimum efficiency is independent of the number of thermocouples in the generator.

The first factor in equation (6) corresponds to the thermodynamic efficiency of a reversible engine, and the second represents the reduction of this efficiency due to losses by thermal conduction and Joule heat. It should be noted that both factors are increased by raising the temperature T_1.

In order to achieve the maximum possible efficiency then, only one condition has to be satisfied, namely, that the materials chosen should have the highest possible value of z compatible with the temperature T_1 of the heat source; that is, $z\frac{(T_1+T_o)}{2}$ should be a maximum. Fig.1 taken from Ref.1 shows a plot of optimum efficiency η against T_1 for various values of z assuming $T_o = 300°K$.

Referring to equation (1), it is usually found for small currents that Q_h is the dominant term in the denominator, thus

$$\eta \simeq \frac{W}{Q_h} = \frac{WL}{JN\,(k_1 S_1 + k_2 S_2)(T_1 - T_o)}$$

where N is the number of thermocouples comprising the generator. Suppose $k_2 = k_1 = k$ and $\rho_1 = \rho_2$ then $S_1 = S_2 = S$ and we have the power output from each thermocouple equal to

$$\frac{W}{N} = \frac{2kSJ\eta\,(T_1-T_o)}{L}.$$

Thus the electrical power generated by each thermocouple depends not upon S and L separately, but only upon their ratio. For a given power required this means that the length of the thermoelements is determined by the area available for heating the hot junctions. Also, the power obtainable per unit volume increases as L^{-2}, and is limited only by the restrictions that the electrical resistance of the junctions must be small compared with the resistance of the arms of the thermoelements, and that the temperature drops between the heat source and the hot junctions of the thermoelements and the heat sink and cold junctions must be small compared with the temperature drop between hot and cold junctions of the thermoelements. There may also be mechanical limitations on the length L imposed by the brittleness of the semiconductor material, and the allowable distortion of the generator due to thermal expansion, since the shorter the arms of the thermoelements, for a given temperature difference between hot and cold junctions, the greater the curvature of the slab of elements forming the generator.

5 THE CHARACTERISTICS OF SOME EXISTING THERMOELECTRIC GENERATORS

The constructional details of thermoelectric generators are only available for some of the early devices which were very inefficient in regard to power output per unit volume. A Russian generator designed to operate a radio receiver from a standard oil lamp gave an output of 1.62 watts at the rate of only 0.01 watt/cc of thermoelectric material (Ref.9), but this was by no means an optimised design. 3000 thermocouples were used in the device, the cross-sectional area of those in the heater circuit being 6.4 × 5.1 mm to carry 0.5 amp at 1.2 volts and those in the anode circuit being 1.6 × 1.6 mm to supply 0.011 amp at 90 volts. The thermoelements were of constantan in the form of braided wire, and zinc antimonide, in proportions 35 Zn : 65 Sb with 3% of Pb to decrease resistivity and increase the strength. The thermoelement blocks were sintered into the form shown in Fig.2 with the separate elements insulated with asbestos lagging. The thermocouple arms were 2.20 cm long and during operation the temperature difference maintained across them was 200°C. Another type of generator of similar size and construction was capable of giving an output of 5 watts (Refs.10, 11). In addition, a generator giving 15-20 watts, again from a kerosene burner, has been produced to feed radio transmitters. The Russians are also manufacturing generators of 200 and 500 watt capacity, and a 100 watt experimental solar thermoelectric generator is already in operation (Ref.1).

An early American device built as a solar thermoelectric generator gave an output of 0.165 watts for a temperature difference of 46°C (Ref.12).

The thermoelements were 2.5 cm in length and comprised bars of zinc antimonide and an alloy of 91 Bismuth 9 antimony. Here the power output per unit volume was only 0.0017 watt/cc, the limiting factor on the size of the thermoelements being the mechanical strength of the alloys.

Recently the Americans have disclosed details (Ref.13) of a 5 watt thermoelectric generator weighing 2.3 kg which is suitable for powering radio transmitters in satellites and rockets. The heat is produced by the absorption of Polonium alpha particles, and the efficiency of convertion of heat into electrical energy is 10%. The device has a smaller surface area than an equivalent solar (photovoltaic) battery.

Recent work on commercial thermoelectric devices has been to produce domestic refrigerators employing the Peltier effect. A Russian water cooled unit (Ref.1) contained around 50 gm of semi-conductor material and consumed approximately 50 watts. Other applications included a thermostatic device for electronic equipment featuring automatic cooling and heating.

In the United Kingdom the only reported work on recent practical devices has been that of an experimental unit for the cooling of individual components of an electrical circuit (Ref.14). Efficiency of operation of the circuit might be lost if all the components had to be maintained at the maximum operating temperature of the most temperature-sensitive component. Bismuth telluride n and p type elements having a figure of merit of $1.1 \times 10^{-3}/^{o}C$ were used. Each element was of dimensions $3 \times 5 \times 7$ mm, and difficulties associated with the extreme brittleness of the material and the adhesion of the copper strips linking the junctions were overcome in this particular design application.

6 THE POSSIBLE APPLICATION OF THERMOELECTRIC DEVICES TO FUZING SYSTEMS IN GUIDED MISSILES

The advantages of thermoelectric devices are that they can be used to convert into useful electrical power heat energy which would otherwise be wasted, they contain no moving parts, they can be tested before use, they should require no servicing after use, and a long operational life may be expected from them. These last two will not be realised in the case of guided missiles, except that deterioration is unlikely to occur during storage. It is anticipated that, when subjected to a dose of nuclear radiation of a sufficient magnitude to render transistors inoperative, thermoelectric devices may still perform satisfactorily. This tentative conclusion is arrived at after a preliminary examination given in Appendix 4.

Thermoelectric devices become a practical proposition when materials of the necessary figure of merit can be fabricated in such a way that the resulting generator will have a weight competitive with conventional D.C. power sources.

A design study is given in Appendix 1 for a 100 watt thermoelectric generator giving an output of 4 amps at 25 volts. The weight of such a generator is shown in Fig.5 as a function of temperature difference between hot and cold junctions, the figure of merit for the thermoelement materials, and the length of the thermoelement arms. By comparison, an existing nickel-cadmium cell, having a weight of 700 gm and a volume of 200 cc, is capable of delivering 120 watts at 20 volts for $2\frac{1}{2}$ to 3 minutes.

From Figs.4 and 5 it can be seen that a 100 watt thermoelectric generator made from materials of a figure of merit of 2.5×10^{-3} and with arms 0.4 cm long supporting a temperature difference of 200°C, would weigh about 600 gm and would have a surface area of hot junctions of 150 sq cm. Assuming a coefficient of expansion of $2 \times 10^{-5}/^{o}C$ for the semi-conductor materials the generator, if in the form of, say, twelve strips 1 cm wide, would bow to a radius of 100 cm.

If each strip were freely supported at say its centre this would involve the edges of each strip moving about 2.0 mm from the quiescent plane. If this movement were restricted by clamping, the thermal stresses set up might be sufficient to cause cracking of the thermoelements. It is possible that this might be overcome to some extent by the use of a plastic material for insulation of the elements.

Appendix 2 describes a hypothetical design for a 100 watt generator which would supply power at 5.6 KV. This is a self-contained unit which derives its thermal energy from an exothermic mixture.

It does appear then that, provided temperature differentials of the order of 200°C or greater are available in missiles, there is a strong possibility that thermoelectric generators, after a comparatively short period of research and development, can compete on a weight-for-weight basis with more conventional sources.

Any powered missile is likely to provide such temperature differentials somewhere in its structure by virtue of its propulsive unit, for example, jet and rocket exhaust pipes and combustion chambers, and it remains to be seen if these can be utilised for thermoelectric generation. The problems to be considered in this application will be the construction and mounting difficulties, the absolute temperature level at which the temperature differential is obtained and the fact that this differential will probably only exist for a short time after "all-burnt".

Another source of heat will be that arising from the hot boundary layer in supersonic flight. Temperature differentials of 200°C will only be set up for speeds in excess of $M = 2.5$ and then for only a brief period unless refrigeration is employed to cool some components in the missile.

In the case of Blue Steel it is known that the navigator and possibly other components will have to be kept cool. For a thermoelectric generator to be applicable it is required that the temperature differential be obtained over as short a distance as possible, in fact, over 1 cm or less. This is rather a severe demand and one of the few locations where it might be satisfied is in the nose.

A ballistic missile does not experience appreciable heating until the re-entry phase when temperatures as high as 1000°C may be encountered on the inner surface of an iron heat shield. The fact that power can only be generated below an altitude of 200,000 ft during the re-entry (temperature gradients are negligible during the ascent) may be useful for transistor supplies or for trigger signals in the fuzing circuit. In the case of an eroding type of heat shield appreciable temperature gradients occur only within the outer ¼ in. of insulating material, and it is doubtful in this case whether a thermoelectric device could be used to give anything other than a triggering signal. This is discussed in detail in Appendix 3.

It should not be forgotten that thermoelectric devices can also be used for refrigerating small components quite economically (Ref.14) (the same criteria hold for their design as for generators) and also for controlling the temperature of, for example, electronic equipment, by regulating the direction of current flow through the thermoelectric elements.

7 CONCLUSIONS

Once engineering and production difficulties have been solved it is possible, using materials which have now been developed, that thermoelectric devices can be produced which will be comparable on a weight-for-weight basis with conventional power supplies. It is conceivable that further development work on materials and manufacturing techniques will lead to devices which will be considerably lighter in weight and more reliable than their conventional counterparts.

The efficiency of thermoelectric devices can only be fully exploited if the hot and cold locations in guided missiles are in close proximity, of order 1 cm, and the successful operation of the devices will depend on there being satisfactorily mounted thermally, electrically and mechanically. The same engineering problems confront the application of thermoelectric materials for refrigeration and thermostatic purposes.

LIST OF SYMBOLS

α thermoelectric power $\frac{\Delta E}{\Delta T}$

η thermoelectric efficiency $\frac{W}{Q}$

k thermal conductivity

σ electrical conductivity

ρ specific resistivity $\frac{1}{\sigma}$

r electrical resistance of a thermocouple

R load resistance

m ratio $\frac{R}{r}$

M optimum ratio $\left(\frac{R}{r}\right)_{opt.}$

Z figure of merit of a thermoelement, $\frac{\alpha^2}{k\rho}$

z figure of merit of a thermoelement "pair", defined in Section 4 of the text

n concentration of carrier electrons or "holes"

u carrier mobility

e electronic charge

W electrical power delivered to load

I current

V voltage

E generator open circuit voltage

N number of thermocouples comprising a generator

LIST OF SYMBOLS (Contd.)

S	surface area
L	length
K	lumped constant, defined in Section 4 of the text
Q	rate of dissipation of heat
T	temperature
J	mechanical equivalent of heat
t	time
τ	time constant
C	capacitance

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APPENDIX 1

OPTIMUM DESIGN FOR A 100 WATT 25 VOLT THERMOELECTRIC GENERATOR

It is assumed that materials which are known to exist and to have values of z of around $2.5 \times 10^{-3}/^{\circ}C$ will be suitable and available for fabrication into compact and optimised thermoelectric generators.

Let the 100 watts be supplied in the form of 4 amps at 25 volts, that is, given a load resistance of 6.25 ohms. Suppose a heat source is available to maintain the hot junctions of the generator at $T_1 = 500^{\circ}K$ and an infinite sink to maintain the cold junctions at $T_o = 300^{\circ}K$.

The optimum ratio of the load resistance R to the internal impedance r is given by:-

$$\left(\frac{R}{r}\right)_{opt} = M = \sqrt{1 + \frac{1}{2} z \, (T_1 + T_o)} = \sqrt{1 + \frac{400 \times 2.5}{10^3}} = 1.414.$$

The maximum efficiency attainable is

$$\eta_{max} = \frac{T_1 - T_o}{T_1} \times \frac{M - 1}{M + \frac{T_o}{T_1}}$$

$$= \frac{200}{500} \times \frac{0.414}{2.014} \times 100$$

$$= 8.22\%.$$

Now we have that the required output from the generator

$$E = I\,(R + r)$$

$$= IR\left(1 + \frac{1}{M}\right).$$

Since the voltage output from each couple is $\alpha\,(T_1 - T_o)$ the total number of couples required is $N = \dfrac{IR\left(1 + \frac{1}{M}\right)}{\alpha\,(T_1 - T_o)}$.

Assuming that the two thermoelectric materials have nearly optimum values for the thermoelectric power, namely $+200\ \mu V/^{\circ}C$ and $-200\ \mu V/^{\circ}C$ respectively, giving $\alpha = 400\ \mu V/^{\circ}C$, we obtain $N = 533$ and $r = \frac{R}{M} = 4.42$ ohms.

If L is the length and S the cross-sectional area of each thermoelement, we have that $r = 2N\rho\,\frac{L}{S}$, where ρ is the mean specific resistivity of the two thermoelectric materials, which is assumed to be 1.0×10^{-3} ohm cm.

Therefore we obtain that $\frac{L}{S} = \frac{4.42 \times 10^{+3}}{1066} = 4.15\ \text{cm}^{-1}$. Fig.4 shows the total surface area occupied by the hot junctions of the generator as a function of the length of the thermoelement arms. An allowance of 50% of the cross-sectional area of the thermoelements was made for the insulation between elements. The estimated weight of the generator is shown in Fig.5 as a function of temperature difference between hot and cold junctions, the figure of merit, and the length of the thermoelement arms. Considering a form of construction similar to that illustrated in Fig.3 the depth of the generator was assumed to be 20% longer than the lengths of the arms to allow for the metal links and insulation.

The overall density of the generator was taken to be 7.2 gm/cc. Table 1 below gives the number of thermocouples for each type of generator and also the dimensions of each thermoelement.

TABLE 1

Figure of merit z per °C	Temperature difference $(T_1 - T_0)$ °C	Number of thermocouples required N	Length of thermoelement arm cm	Cross-section of each thermoelement assumed square of side cm
1×10^{-3}	100	1790	0.3 1.0 2.0	0.32 0.58 0.82
	200	890	0.3 1.0 2.0	0.23 0.41 0.58
	300	590	0.3 1.0 2.0	0.18 0.34 0.48
2.5×10^{-3}	100	1080	0.3 1.0 2.0	0.38 0.69 0.97
	200	530	0.3 1.0 2.0	0.27 0.49 0.70
	300	350	0.3 1.0 2.0	0.22 0.41 0.57

APPENDIX 2

DESIGN FOR A 100 WATT, 5.6 KV THERMOELECTRIC GENERATOR

Such a generator might be used to charge storage capacitors directly, thus obviating the need for an invertor-transformer set.

A typical charging circuit is shown in Fig.6 where C and R are the load capacitance of 18 µF and leakage resistance of 50 MΩ, respectively. A maximum transfer of power to the capacitor of 100 watts will be obtained 1 second after connecting the 5.6 KV generator to the load if the internal resistance r of the generator is 80 KΩ. The time constant of the circuit is then 1.4 seconds. It should be noted that this is the condition for maximum power transfer to the load, not the maximum power dissipated by the generator which is instantaneously 400 watts when the load is connected to the generator.

Assuming again that thermoelectric materials of figure of merit $z = 2.5 \times 10^{-3}/^{o}C$ are available, for which $\alpha = 200\ \mu V/^{o}C$, $\rho = 10^{-3}\ \Omega$ cm and $k = 3.83 \times 10^{-3}$ cal/cm/sec/°C. The number of thermocouples required to generate 5.6 KV for a 200°C temperature differential is 70,000, and $\frac{L}{S} = \frac{r}{2N\rho} = 560\ cm^{-1}$. The cross-sectional area of each thermoelement is $1.8 \times 10^{-3}\ cm^2$ if the elements have length L = 1 cm. The total surface area of the hot junctions, allowing a 50% increase in area for insulation, is $375\ cm^2$.

A cylindrical generator having these properties is illustrated in Fig.7. The heat source in this case is a chemical cartridge of exothermic "heat paper" which, when fired, will reach a maximum temperature of around 450°C.

The resulting temperature differential across the thermoelements, the cold junctions of which are cooled by means of natural convection and radiation, will be of the same form as that shown for the output of the generator in Fig.8.

Since the capacitor voltage will lag behind the generator voltage, it will be necessary for the latter to exceed 5.6 KV for at least 7 seconds to ensure that the capacitors are fully charged, i.e. the temperature differential of 200°C must be maintained for this period. By suitable arrangement of insulation between the "heat paper" and the hot junctions of the thermoelements, and disposition of annular fins attached to the cold junctions, a design could be achieved giving an optimum period for the generator to deliver power at 5.6 KV without the maximum voltage output being unduly high. This, however, will be associated with a longer charging time before the capacitors reach their working voltage.

The design of a generator of this type is hardly practicable at this stage of development from the standpoint of fabrication of the thermoelements, but it is of interest to note that in theory such a generator is possible.

APPENDIX 3

THE POSSIBLE USE OF A THERMOELECTRIC CONTROL SIGNAL IN THE FUZING SYSTEM OF A BALLISTIC MISSILE

(The quantitative information on which this appendix is based has been provided by G.W. Dept., R.A.E.)

The heating of a ballistic missile during re-entry into the atmosphere will be determined by whether a high or low drag head is used and whether the heat shield is fabricated from durestos or steel. The temperatures and temperature gradients achieved in the structure will depend on the thermal capacity and thermal diffusivity of the material of the shield, and on the state of the boundary layer at the point considered.

(1) Heat sink head

A metal heat sink shield is practicable only for a high drag head and Fig.9 shows a plot of the inside temperature of an Armco iron heat shield (0.3 in. thick) at the point of maximum heating, together with the temperature differential across its thickness at the same point. This is compared with the deceleration of the vehicle, and it can be seen that the shape of the temperature differential curve is similar to that of the 'g' curve, the peaks occurring at about the same time. The magnitude of the temperature levels is very dependent on the boundary layer transition point and the example given is an extreme case assuming a turbulent boundary layer over the whole of the heat shield. By anticipating a reasonable amount of laminar flow (transition Reynold's number 1×10^6), the maximum temperature differential is 270°C at which time the temperature of the inside surface is 441°C. The data presented in Table 2 below include values for the stagnation point where temperatures may most accurately be predicted.

TABLE 2

Time of re-entry from 200,000 feet secs.	State of boundary layer	Peak differential across shield		Peak temperature on inside of shield		Time from re-entry at which peak 'g' occurs secs.
		Value °C	Time from re-entry secs.	Value °C	Time from re-entry secs.	
132	Fully turbulent 45° pt.	350	12	1031	15.5	11
	Partly turbulent 45° pt.	270	12.1	753	20	
	Stagnation pt.	110	10.5	535	20.5	

Owing to the number of variables present and the limitation on the number of trials rounds, it seems probable that temperatures could not be sufficiently well predicted to enable a thermoelectric signal to provide a burst function, as distinct from an initiation of the arming sequence for which accurate timing is not so essential. The latter scheme has the advantage from the standpoint of safety that the threshold of the triggering signal may be arranged so that it is only effective if the nose cone enters the atmosphere at approximately the correct speed. Such a device would have to function satisfactorily in conditions giving rise to the minimum expected heating and preferably to withstand the maximum expected temperatures.

Any attempt to sense the temperature differential across the heat shield would involve some disruption of the shield itself in order to install the thermopile. This may not be acceptable and, therefore, a monitor of the temperature of the inside of the heat shield seems most promising. Temperature differentials arising in the internal structure will probably occur too late, and will probably be too small, to be useful.

As the source of power is virtually limitless, we are not concerned with optimising the efficiency of a thermopile, but rather with ensuring good mechanical and electrical reliability. Here the thermocouple principle is in competition with other methods of temperature sensing, but it is attractive since it requires no electrical power supply, it has no moving parts, and it is inherently "safe", i.e. relatively insensitive to external conditions. Using chromel-alumel thermocouple materials to detect a temperature rise of 500°C by giving a power output of 2 watts at 6 volts, 300 welded junctions would be required and, for an element length of $\frac{1}{2}$ inch, 25 S.W.G. wire would be needed. It should be pointed out that all the hot and cold junctions must be electrically insulated from the metal heat shield and this might be expected to present an installation problem.

(2) Eroding head

A low drag re-entry head of durestos or similar material will be subject to erosion, and an error in the predicted rate of erosion will greatly affect the estimated progress of the temperature profile through the material.

Fig.10 shows the temperature profile at various times after re-entry through the thickness of a durestos skin for a relatively severe heating case. Durestos offers the possibility of moulding thermocouples into the skin, with no problem of insulation, and the temperature differentials across a $\frac{1}{4}$ inch length within the skin thickness are indicated in Fig.10 at various times after re-entry. The low drag nose will be conical with a rounded tip in contrast to the hemispherical shield for the heat sink case, and the ablation which will occur towards the nose will tend to cause a build up of material aft of the nose. Any temperature or erosion sensing device should therefore be located fairly near the stagnation point. Experience gained during trials of the suitability of such devices as resistance wire, alpha particle sources and pressure transducers should indicate whether any of these possibilities might also be considered for initiating the arming operations.

APPENDIX 4

THE EFFECT OF NUCLEAR RADIATION ON THE PERFORMANCE OF A THERMOELECTRIC DEVICE

In view of the susceptibility of semi-conductor devices, such as transistors, to permanent damage by nuclear radiation and of the high efficiency of photovoltaic energy conversion of semi-conductor barrier cells, it is necessary to examine the effects of nuclear radiation on semi-conductor type thermoelectric generators.

It is well known (Ref.15) that permanent damage to semi-conductor devices, such as transistors, is due to the production of Frenkl-type defects in the crystal lattice which leads to decay of the minority carrier life-time in the base region and so to reduction of the current gain. Usually no attempt is made to construct thermoelectric junctions from single crystal material having few lattice defects, and therefore it is unlikely that such generators would be damaged by a neutron dose of a magnitude which would render a transistor useless viz. 10^{13} neutrons/cm^2.

A proportion of atoms in the thermoelectric material will interact with the incident neutrons. Assuming that a thermoelectric generator 1 cm thick receives a dose of 10^{16} thermal neutrons/cm^2, only about 5×10^{-4}% of the atoms present will interact with neutrons, and there should be negligible effect on the efficiency of the generator. It is known also that insulating materials do exist which will withstand this amount of radiation.

Consider now the transient effects; these may be of two types, (1) the photovoltaic effect in which the energy of the neutron dose is converted directly into electrical energy, and (2) the thermoelectric effect in which neutron absorption sets up an instantaneous temperature gradient which gives rise to a spurious thermoelectric signal. Again, assuming a dose of 10^{16} neutrons/cm^2 having energy 1 MeV, but having a capture cross-section appropriate to thermal neutrons, a temperature difference of 30°C might be set up momentarily across a generator 1 cm thick, whilst the mean temperature of the device might rise by 180°C.

A gamma ray dose equivalent to 10^6 rontgens with photons of mean energy 3 MeV may give rise to a momentary temperature differential of 12°C across a thermoelectric device 1 cm thick and the mean temperature may rise by 45°C.

Thus a very tentative examination shows that, although the temperature of the thermoelectric devices might rise to dangerously high levels when subject to nuclear radiation, it may be possible to distinguish a steady build-up of output signal due to, say, kinetic heating of a missile from the spurious transient signal due to the photoelectric and thermoelectric effects of a dose of nuclear radiation. However, further investigation would be needed to confirm this conclusion.

APPENDIX 5

THE PRESENT STATUS OF WORK ON THERMOELECTRIC DEVICES IN U.K.

Two large organisations are known to be engaged on the development of semi-conductor materials for thermoelements. At present only a small amount of work has gone into the engineering of refrigerating devices for the commercial market, and, as far as can be ascertained, practically no effort has been devoted to the production of generators.

The Plessey Co. Ltd. has manufactured materials with a figure of merit of $0.9 \times 10^{-3}/^{o}C$, and is interested in pursuing this line if given financial encouragement.

The General Electric Company's Research Laboratories at Wembley have been working in this field for some considerable time, and are at present producing samples having a figure of merit of $2.4 \times 10^{-3}/^{o}C$ for experimental purposes. Members of their team have had their work well documented in the recent literature (1954-58), and from this it appears that they are at least on a par with the work in this field in the United States.

It is known that the Admiralty is interested in supporting work on the development of thermoelectric devices and they have suggested that this work be carried out at S.E.R.L. Baldock. It is understood that the F.V.R.D.E. is about to place a contract with G.E.C. to develop devices for fighting vehicles.

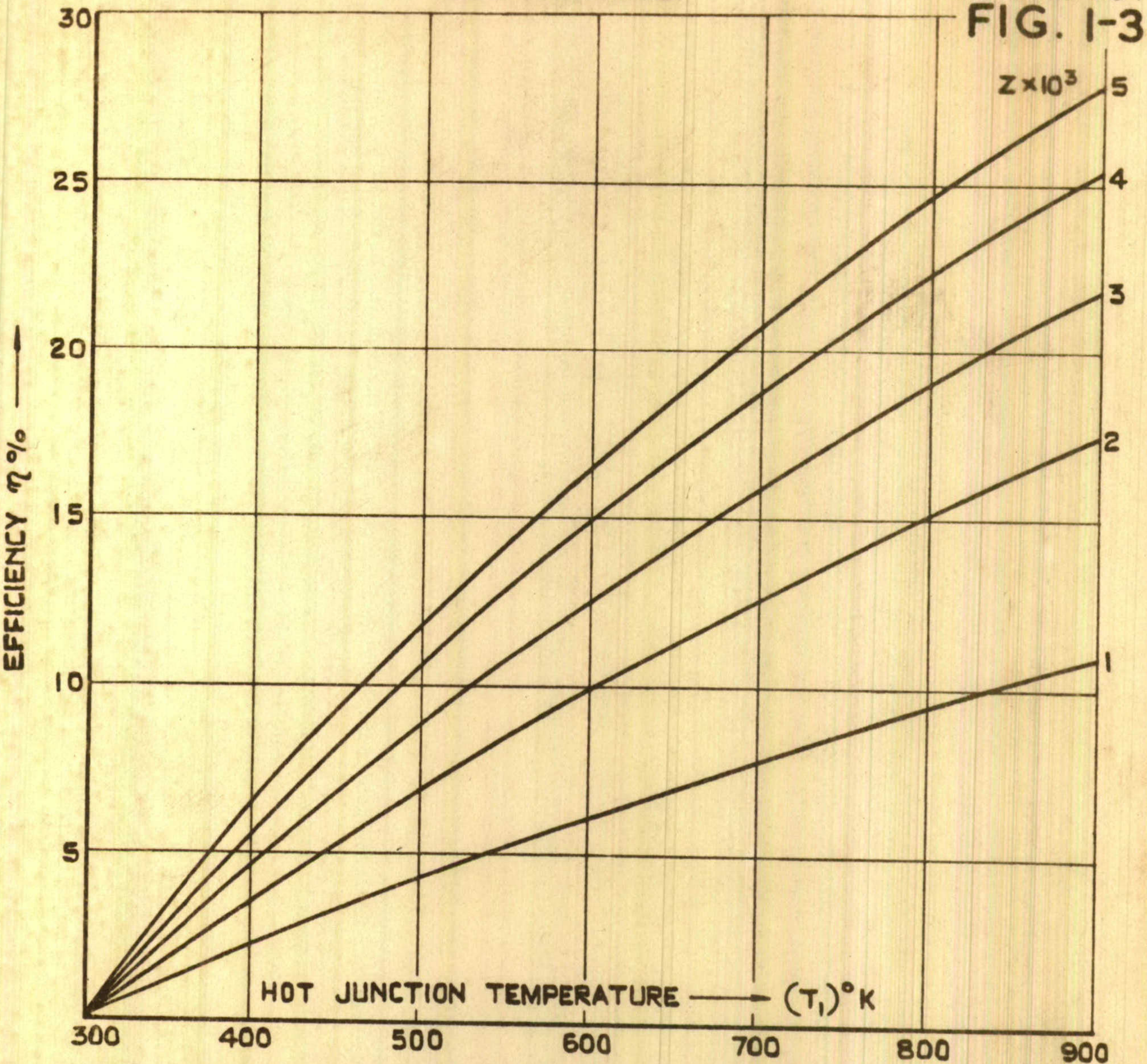

FIG.1 THE EFFECT OF HOT JUNCTION TEMPERATURE AND FIGURE OF MERIT ON THE EFFICIENCY OF THERMO-COUPLES.

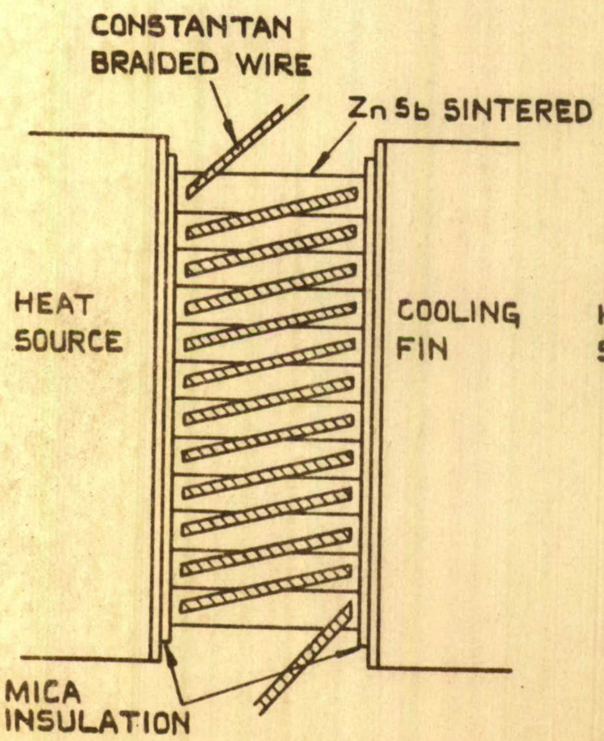

FIG. 2 CONSTRUCTION OF RUSSIAN THERMOELECTRIC GENERATOR TEGK-2-2.

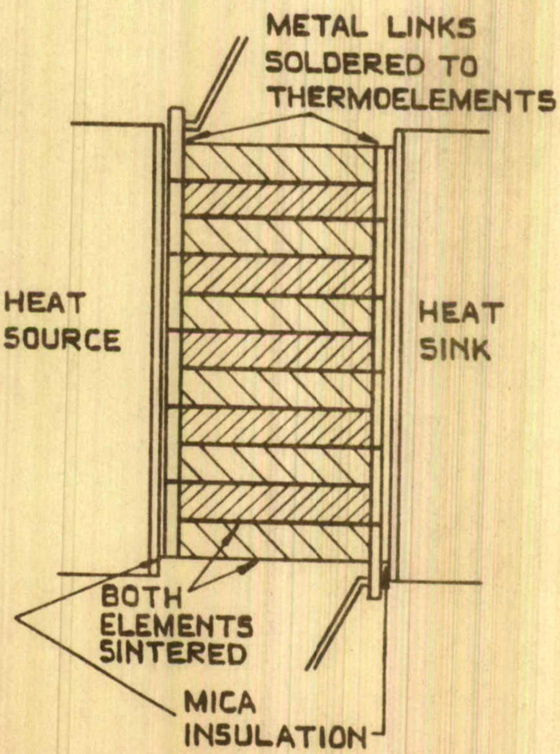

FIG.3 TYPICAL CONSTRUCTION FOR THE CASE OF BOTH THERMOELEMENT ARMS FORMED BY SINTERING.

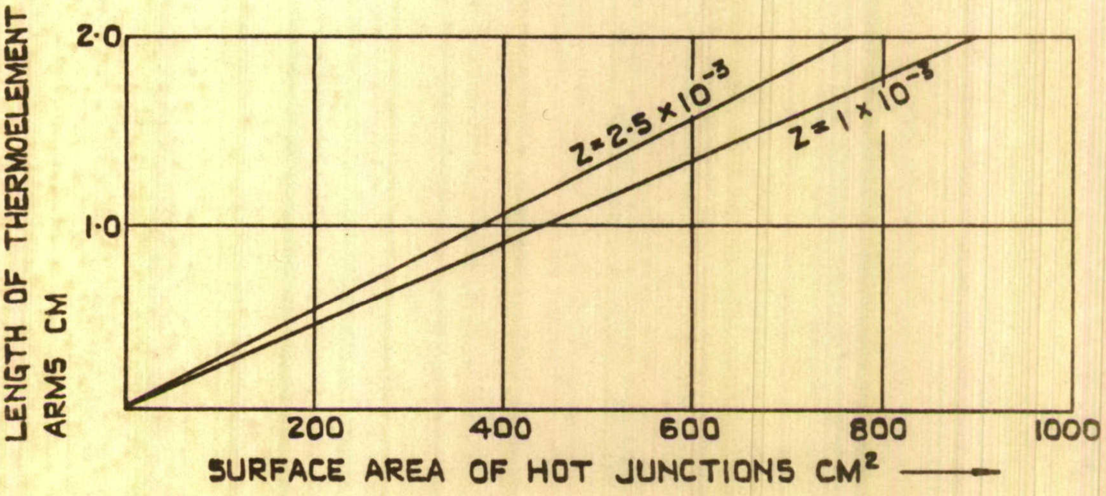

FIG. 4. OPTIMUM DIMENSIONS FOR A 100 WATT 25 VOLT THERMOELECTRIC GENERATOR WITH A TEMPERATURE DIFFERENCE $(T_1 - T_0)$ OF 200°C.

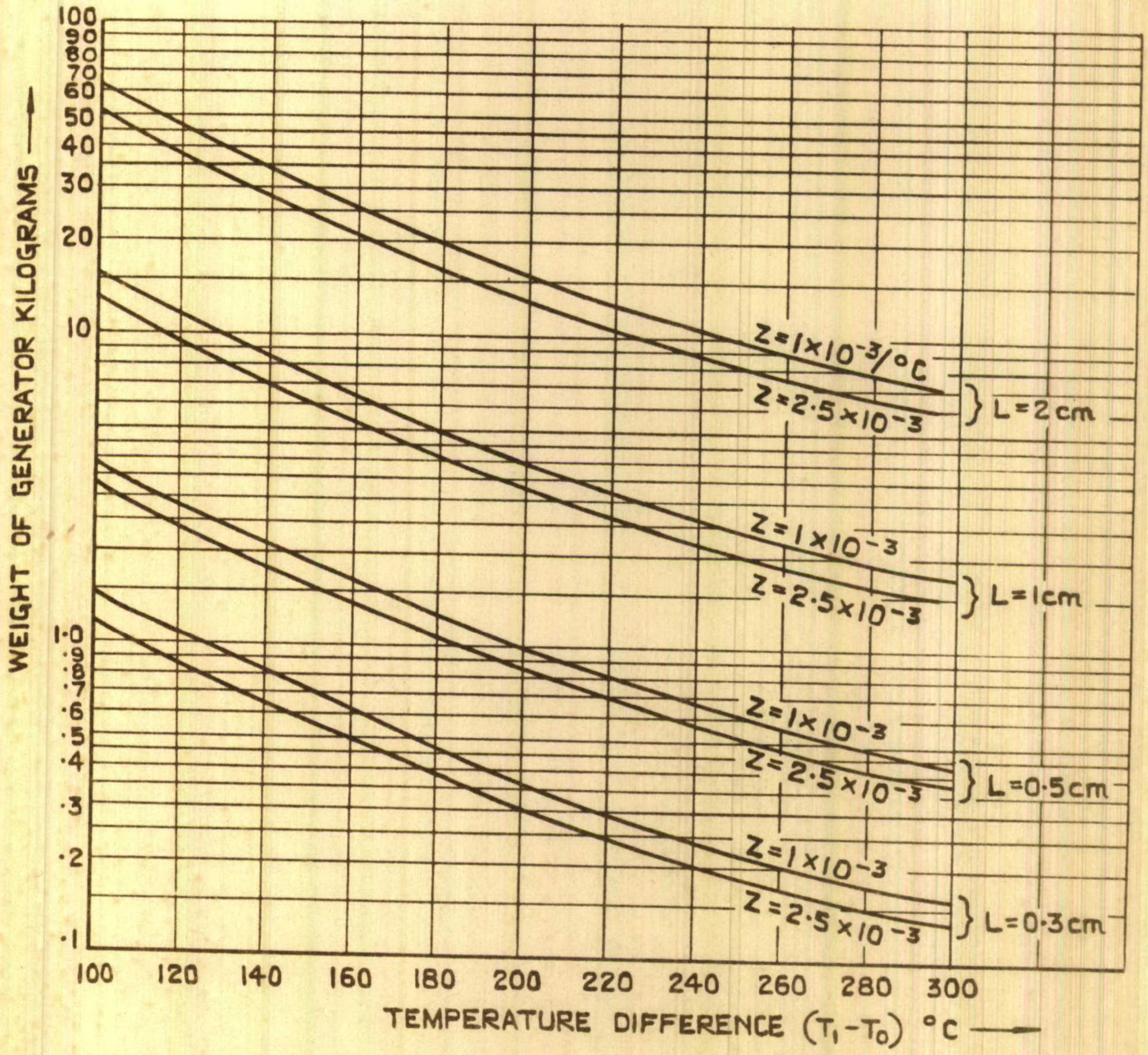

FIG. 5 DESIGN FEATURES OF A 100 WATT 25 VOLT THERMOELECTRIC GENERATOR.

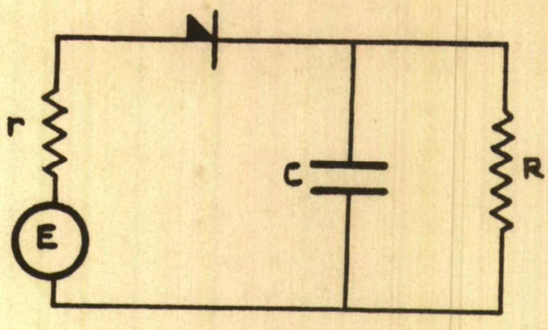

FIG. 6. CHARGING CIRCUIT FOR STORAGE CAPACITORS.

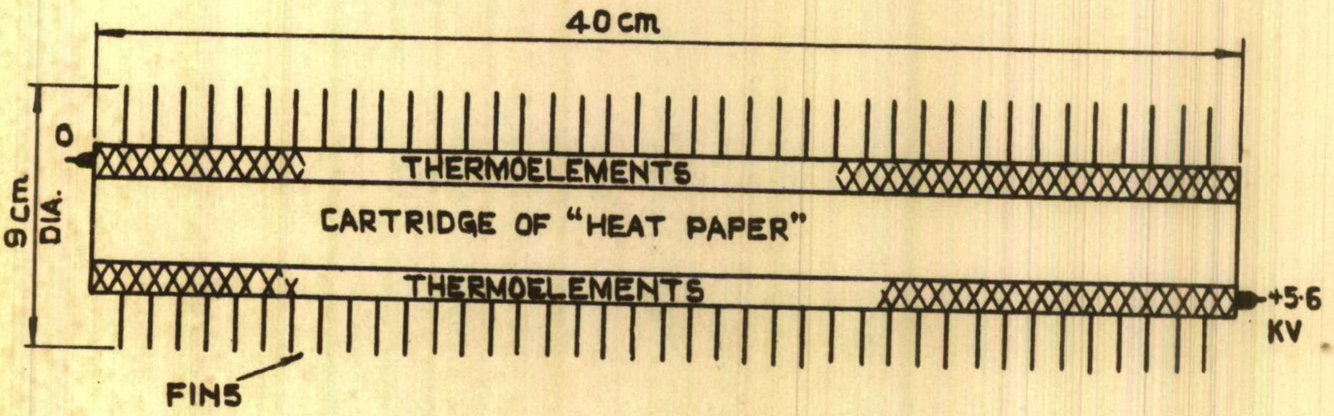

FIG. 7. HYPOTHETICAL 100 WATT 5·6 KV THERMOELECTRIC GENERATOR

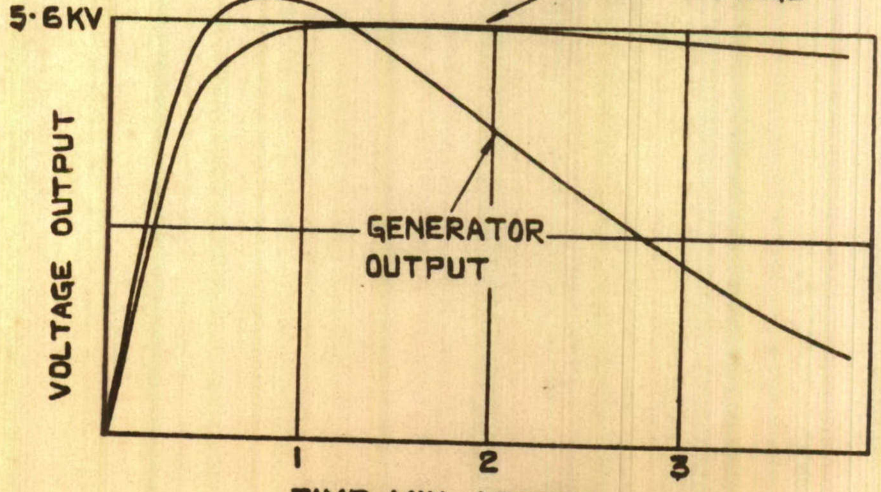

FIG. 8. CHARACTERISTICS OF CHARGING CIRCUIT USING A THERMOELECTRIC GENERATOR.

FIG. 9.

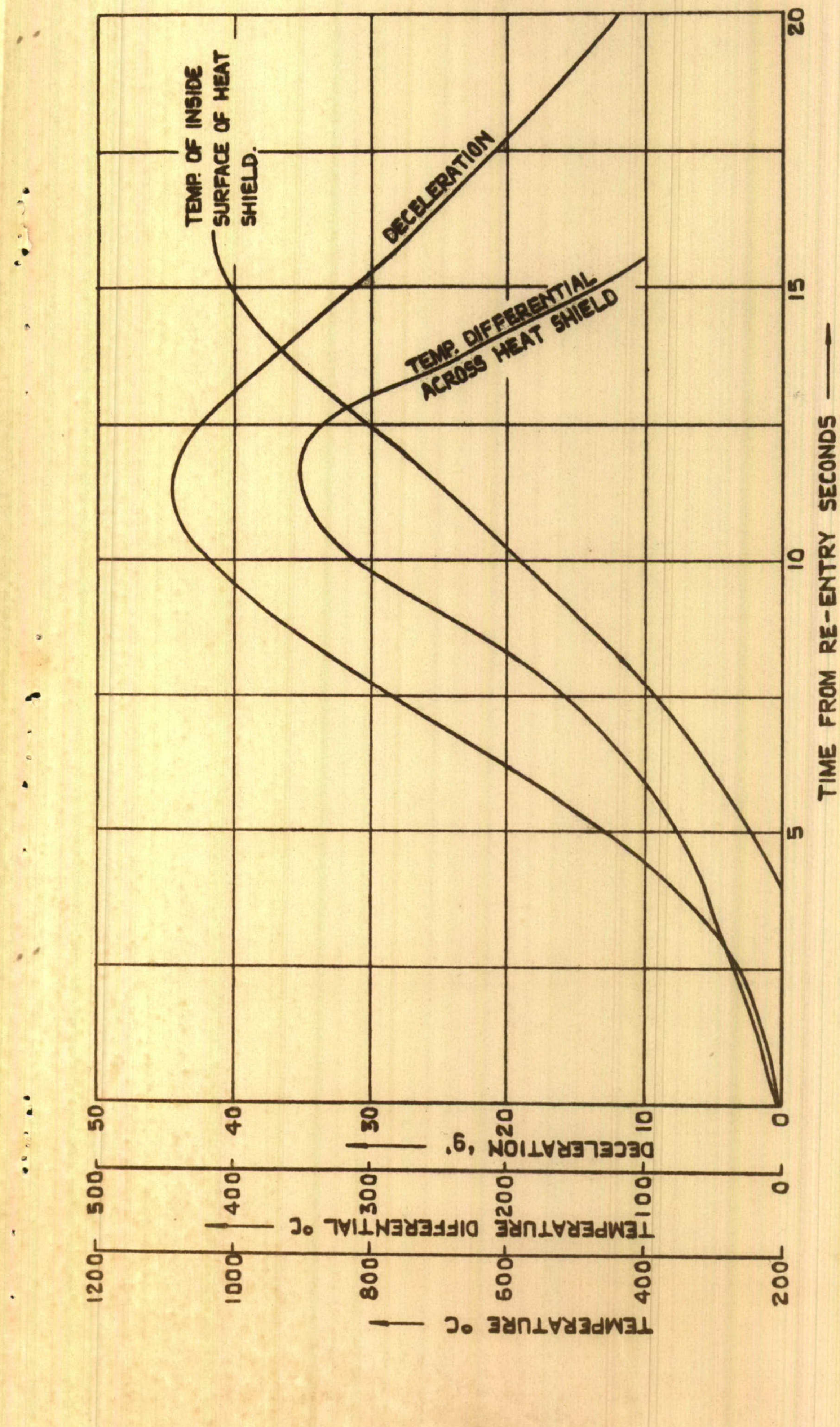

FIG. 9. RE-ENTRY OF A HIGH DRAG BALLISTIC MISSILE WITH A HEAT SHIELD OF 'ARMCO' IRON 0·3 INCH. THICK.

FIG. 10

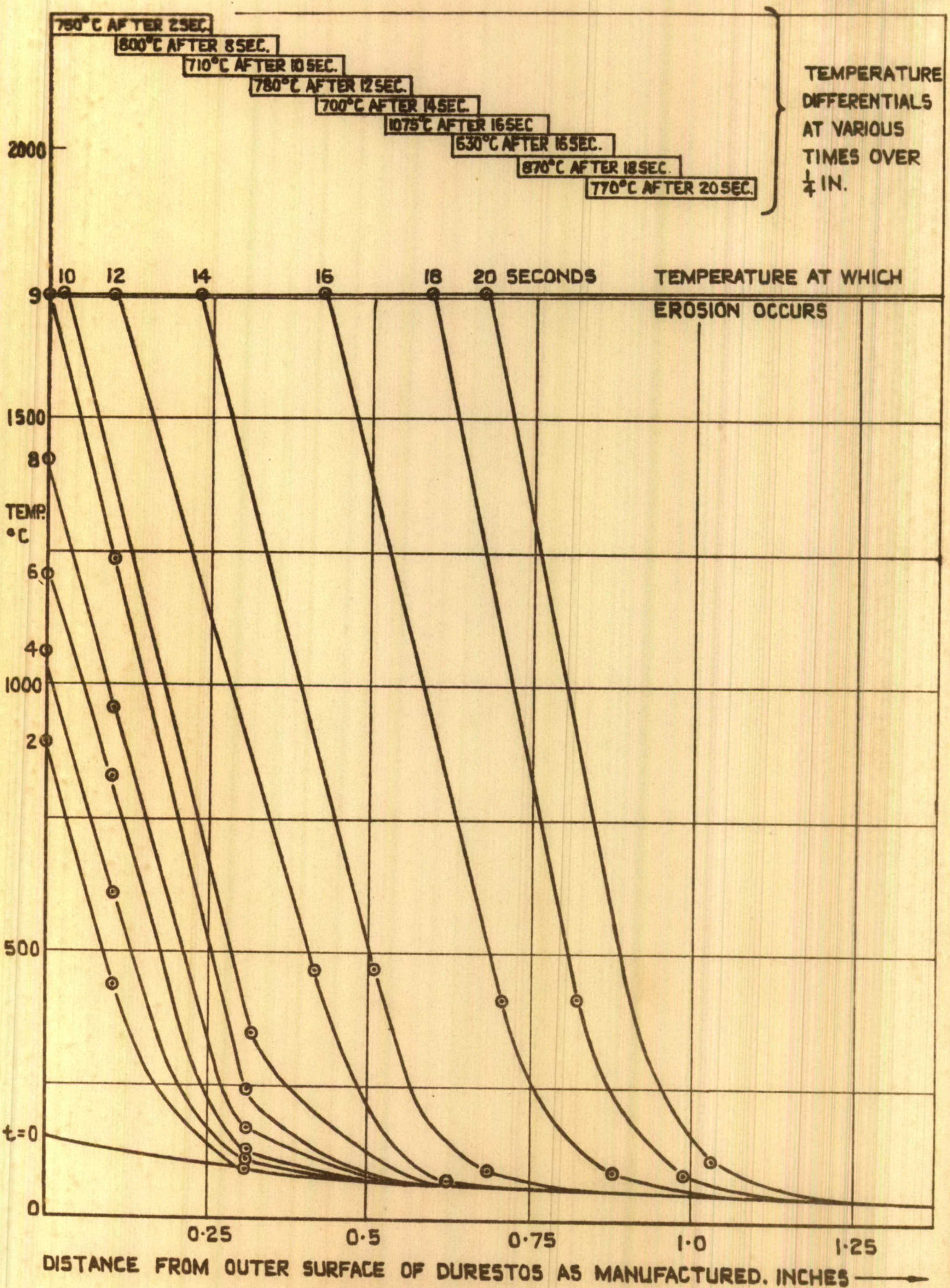

FIG. 10 TEMPERATURE PROFILES THROUGH A DURESTOS SKIN DURING RE-ENTRY OF A LOW DRAG HEAD AT A TYPICAL POINT IN TURBULENT FLOW. INITIAL THICKNESS OF SKIN IS 1·45 INCHES.

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Record Summary: AVIA 6/17287
Title: Application of thermoelectric devices to guided missile fuzes
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
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